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(54) APPARATUS FOR DETECTING THE ORIENTATION OF THE PLANE OF POLARISATION OF A LINEARLY POLARIZED BEAM OF RADIATION

(71) We, PHILIPS ELECTRONIC AND ASSOCIATED INDUSTRIES LIMITED, of Abacus House, 33 Gutter Lane, London, E.C.2, a British Company, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to apparatus for detecting the orientation of the plane of polarisation of a linearly polarised beam of radiation by means of a radiation-sensitive detection system.

In one form of such apparatus hitherto proposed, the intensity of the radiation is measured after the linearly polarised incident beam has traversed an analyser. This intensity is then taken as a measure of the position of the plane of polarisation.

In another proposed form of such apparatus, a beam splitter is arranged in the path of the linearly polarised incident beam to split the beam into two parts, and a respective polariser is so arranged in the path of each of the beam portions that the directions of polarisation of the two polarisers are effectively at an acute angle to each other. The beam splitter can, for example, be a semi-transparent beam splitter. Each polariser passes only that component of the incident radiation which is polarised in the direction of polarisation of the respective polariser. If the beam splitter splits the beam into two equal parts and the directions of polarisation of the polarisers are effectively at an angle to each other of 45° with reference to the orientation of the polarisation of the beam, the sum of the squares of the amplitudes of the radiation passed by each of the polarisers is constant. Each beam portion can then be directed onto a respective quadratic detector, the electrical output signal obtained from each detector being proportional to the square of the amplitude of the radiation incident thereon. The respective detector output signals can be applied, preferably after amplification, to the horizontal and vertical deflection plates of a cathode-ray tube, and a spot can thereby be displayed on the screen of the tube, which describes a circular path and will execute one complete revolution thereof if the direction of polarisation of the linearly polarised beam of radiation is rotated through 180°.

The detection arrangements hitherto proposed suffer the disadvantage that only comparatively rapid variations in the orientation of the plane of polarisation of the linearly polarised beam of radiation can readily be measured. For if the orientation of the plane of polarisations does not vary or varies only slowly, the output signal of the radiation-sensitive detection system will be a direct voltage or a slowly varying voltage. This direct voltage or slowly varying voltage must be processed, and this involves difficulties.

It is an object of the invention to provide improved apparatus of the kind set forth in which the measurement of a stationary or slowly varying orientation of the plane of polarisation is facilitated.

In accordance with the invention there is provided apparatus for detecting the orientation of the plane of polarisation of an incident beam of linearly polarised radiation by means of a radiation-sensitive detection system, comprising radiation-sensitive detection means to provide an output dependent on the orientation of the plane of polarisation of radiation incident thereon, and a series-combination of at least three doubly-refracting elements, at least one of which is an electro-optical crystal to which a varying electrical voltage is applied, said series combination being arranged in the path of said incident beam prior to said detection means, the relative orientation of said elements and the electrical voltages applied to said electro-optical crystal or crystals being such that whereas the radiation falling on said detec-

tion means is maintained substantially linearly polarised, the orientation of the plane of polarisation is periodically varied with reference to the orientation of the polarisation of said incident beam to facilitate the determination of a stationary or slowly varying orientation of the polarisation of said incident beam. Thus, a dynamic detection of a static or quasi-static state can be obtained.

The series-combination can comprise two λ/4-plates between which is arranged an electro-optical crystal to which an alternating electric voltage is applied and a principal direction of which is at an angle of 45° to the principal directions of each of the λ/4-plates.

Herein the principal direction of a λ/4-plate will be used to denote one of the two orthogonal directions transverse to the propagation direction of electromagnetic waves, representing the direction of polarisation of an electromagnetic wave propagating respectively as a fast or as a slow wave, and the principal direction of an electro-optical crystal will be used to denote one of the two directions transverse to said electromagnetic wave propagation direction corresponding to respective principal dielectric axes.

The electro-optical crystals used are preferably crystals exhibiting the Pockels effect. The birefringence of these crystals is a linear function of the voltage applied to the crystals. An example of such a crystal is a KDP-crystal which is electro-optically very stable and is relatively easy to handle. The dielectric properties of a KDP-crystal allow relatively high frequencies and high voltages to be used. Such a crystal can therefore be deeply modulated at a high frequency.

As an alternative, crystals can be used whose birefringence is proportional to the square of the applied voltage. An example of such a crystal is a KTN-crystal. When such a crystal is supplied with a voltage which is the sum of a direct voltage and a small alternating voltage, the birefringence can be made to vary substantially linearly with the instantaneous amplitude of the alternating voltage.

If polarised radiation is passed through the aforesaid crystals, the state of polarisation of the radiation can be changed so that the state of polarisation of the emergent radiation will vary in accordance with variations of the voltage applied to the crystal.

In order that the invention may be clearly understood and readily carried into effect embodiments thereof will now be described by way of example with reference to the accompanying drawings, of which:

Figure 1 is a schematic diagram showing one embodiment of an apparatus employing the invention,

Figures 2a, 2b and 3 are geometric representations of the states of polarisation of a radiation wave illustrating the operation of the arrangement of Figure 1,

Figure 4 is a schematic diagram illustrating means for processing the signals obtained from the apparatus shown in Figure 1,

Figure 5 is a schematic diagram showing a second embodiment of the arrangement according to the invention, and

Figures 6a, 6b and 6c are geometric representations of the states of polarisation of a radiation wave illustrating the operation of the arrangement of Figure 5.

In the arrangement of Figure 1, the reference numeral 1 denotes a light source emitting linearly polarised radiation, for example, a saccharimeter. The linearly polarised radiation emitted from the light source 1 and converted by the lens 2 into a parallel beam is incident upon the series-combination of a λ/4-plate 4, a KDP-crystal 5 and a λ/4-plate 6. The principal directions 7 and 9, as herein defined, of the λ/4-plates 4 and 6 are parallel to each other, whilst the principal direction 8, as herein defined, of the crystal 5 is at an angle of 45° to the principal directions of the plates 4 and 6.

An alternating voltage $V - V_0 \sin \omega t$ is applied to the crystal 5 so that the electric field produced by the voltage in the crystal is parallel to the direction of propagation of the radiation in the crystal.

The state of polarisation of the light emitted from the series-combination comprising the λ/4-plate 4, the crystal 5 and the λ/4-plate 6 can be readily illustrated by means of the Poincaré sphere which represents all the states of polarisation of a radiation wave, cf. also "Principles of Optics" by Born and Wolf, pages 30 and 31.

Referring to Figure 2, a state of polarisation P can be characterized by an ellipse in the xy-plane, the major axis L of which is at an angle ϕ to the x-axis, and the diagonal D of the circumscribed rectangle is at an angle ζ to L. The ratio of the axes of the ellipse is given by $\tan \zeta$.

On the Poincaré sphere shown in Figure 2b, the point P is characterized by the angles 2ϕ and 2ζ. There is thus an unambiguous relation between the state of polarisation and the associated point on the sphere.

For linearly polarised light, as can be seen from Figure 2a the angle $\zeta = 0°$, and this condition corresponds to points on the equator of the sphere, that is to say that the equator represents all the states of linear polarisation.

For circularly polarised light the angle $\zeta = 45°$, and this condition corresponds to the poles A_1 and A_2 of the sphere.

A linear phase anisotropy occurring in birefringent crystals can be represented as a rotation about an axis in the plane of the equator.

On the Poincaré sphere shown in Figure 3, the line FG represents the principal direction of the $\lambda/4$-plates 4 and 6 and the line ED indicates the principal direction of the crystal 5.

An arbitrary orientation is chosen for the plane of polarisation of the radiation incident upon the $\lambda/4$-plate 4. The line B_0O, which is at an angle α^1 to the axis FG, represents this arbitrary orientation.

For any arbitrary time t, the change of the state of polarisation of the incident polarised radiation caused by the $\lambda/4$-plate 4 is represented by a rotation about the axis FG through 90°. The point B_1 on the circle TFSG represents the state of polarisation of the radiation emerging from the $\lambda/4$-plate 4.

In the case of the crystal 5, the state of polarisation of the emergent radiation will vary with reference to that of the incident radiation in accordance with the instantaneous voltage applied to the crystal. At the instant $t=0$, $V=0$. The crystal 5 does not influence the incident light. The point B_1 consequently also represents the state of polarisation of the radiation emerging from the crystal 5.

At the instant $t=T/4$ where T is the period of the modulation applied to the crystal 5, $V=V_0$. The crystal 5 changes the state of polarisation of the light incident thereon. The point B_2 on the circle TFSG obtained by rotation about the axis DE represents the state of polarisation of the radiation emerging from the crystal 5.

At the instant $t=T/2$, $V=0$. The point B_1 represents the state of polarisation of the radiation emitted from the crystal 5.

At the instant $t=3/4$ T, $V=-V_0$. The crystal 5 changes the state of polarisation of the light incident thereon. The point B_3 on the circle TFSG represents the state of polarisation of the radiation emerging from the crystal 5.

The $\lambda/4$-plate 6 changes the state of polarisation of radiation incident thereon. This change is represented by a rotation through 90° about the axis FG. The points B_4, B_5 and B_6 on the equator represent at the instants $t=0$ and $t=T/2$, at the instant T/4 and at the instant 3/4 T, respectively, the state of polarisation of the linearly polarised radiation emerging from the $\lambda/4$-plate 6. The motion of the point B_4 as it passes to and fro along the equator between the points B_5 and B_6, is harmonic, because the voltage applied to the crystal 5 is sinusoidal.

The orientation of the azimuth of the radiation emerging from the $\lambda/4$-plate 6 is represented by $\alpha=\alpha_0+\beta\sin\omega t$, in which α_0 represents the position of the plane of polarisation relative to an arbitrary plane at the instant $t=0$ and β represents the amplitude of the angle of rotation of the plane of polarisation caused by the crystal 5.

The linearly polarised radiation emerging from the $\lambda/4$-plate 6 and having an azimuth $\alpha=\alpha_0+\beta\sin\omega t$ is directed onto the semi-transparent beam-splitter 20 and thence onto the polarisers 21 and 22, respectively. The directions of polarisation 23 and 24 of the polarisers 21 and 22 are inclined at an angle to each other of 45° when referred to the orientation of the polarisation of the respective beams. The intensity of the radiation emerging from the polariser 21 and that of the radiation emerging from the polariser 22 together determine unambiguously the instantaneous position of the plane of polarisation of the radiation emergent from the $\lambda/4$-plate 6.

The radiation is converted by the detectors 33 and 34, respectively, into an electric voltage having a waveform represented by

$$S_1 = \text{constant} + S\sin 2(\alpha_0+\beta\sin\omega t), \text{ and}$$
$$S_2 = \text{constant} + S\cos 2(\alpha_0+\beta\sin\omega t),$$
respectively.

In the following manner described with reference to Figure 4, an indication can be obtained from these voltages. If the amplitude β is chosen to be small, for example, 0.2 radian, a close approximation of the above formulae can be obtained by re-writing the expressions as

$$S_1 = \text{constant} + S\sin 2\alpha_0 + 2\beta\cdot S\cos 2\alpha_0 \sin\omega t.$$
$$S_2 = \text{constant} + S\cos 2\alpha_0 - 2\beta\, S\sin 2\alpha_0 \sin\omega t.$$

Referring now to Figure 4 the electrical signals from the detectors 33 and 34 are applied to the devices 35 and 36, to which are also applied voltages from sources 40 and 41 respectively, which are proportional to $\sin\omega t$. The product of the applied voltages is formed in the devices 35 and 36 each comprising, for example, a Hall generator. The mixed products are applied to the low-bandpass or low-pass filters 37 and 38, which pass signals of, for example, $\frac{1}{2}\omega$. Voltages proportional to $\cos 2\alpha_0$ and to $\sin 2\alpha_0$, respectively, are then produced at the filter outputs and can be further processed as desired.

It will be apparent that the electrical signals S_1 and S_2 from the detectors 33 and 34 can be processed not only in the manner described hereinbefore which is further described in British Patent Specification No. 997,405, but also in other ways, one example of which is also described in the aforesaid British Patent Specification No. 997,405.

As an alternative to the simple harmonic rotation described above, a linear rotation may be imparted to the plane of polarisation of the linearly polarised beam of radiation which is directed onto the beam split-

ter 20. The output signals produced by the radiation-sensitive detectors 33 and 34 will then have a comparatively simple waveform. Figure 5 shows an embodiment of apparatus in which the plane of polarisation can be rotated at a constant angular speed.

In the arrangement of Figure 5, the linearly polarised beam of radiation emitted from the light source 51 and converted by the lens 52 into a parallel beam is incident upon the series-combination of three KDP-crystals 54, 55 and 56. The principal directions 61 and 63 of the crystals 54 and 56 are parallel to each other and the principal direction 62 of the crystal 55 is at an angle of 45° to the principal directions 61 and 63 of the respective crystals 54 and 56. To the crystals 54 and 56 is applied an alternating voltage $V_1 = V \sin\omega t$ from the alternating voltage source 58, whilst an alternating voltage $V_2 = V^1 \cos\omega t$ from the alternating voltage source 59 is applied to the crystal 55. The voltages V and V^1 are applied so that the field strength produced by the voltage in the crystals 54 and 56 and in the crystal 55, respectively, is parallel to the direction of propagation of the light in the respective crystal.

The amplitude V is arranged to be such that linearly polarised light incident upon each of the crystals 54 and 56, respectively, is converted by this voltage into circularly polarised light and this means that a phase difference of one quarter wavelength is produced between the two waves formed from the linearly polarised light as it traverses the respective crystal.

The peak voltage V^1 is arranged so as to produce a phase difference of a half wavelength between the two waves formed from linearly polarised light as it traverses the crystal 55, in other words the light emerging from the crystal 55 would in this instance still be linearly polarised.

The orientation of the plane of polarisation of the emergent light can be readily calculated for five instants in time.

For the five instants $t=0$, $t=\frac{1}{8}$ T, $t=\frac{1}{4}$ T, $t=\frac{3}{8}$ T and $t=\frac{1}{2}$ T, the orientation of the plane of polarisation is rotated approximately in proportion to the time t. For intermediate instants, there are deviations from this direct proportionality. The angular velocity of the plane of polarisation is therefore only approximately constant. Moreover, the light emerging from the series-combination of crystals is slightly elliptically polarised at intermediate instants. By a more selective choice of the voltages V and V^1 and alternatively or additionally, by employing a series sequence of $(2n+1)$ crystals, where n is an integer, to which an appropriate excitation is applied, the approximation to a constant velocity of rotation and of the linear polarisation of the light throughout the rotation can be improved. In the latter case, the odd- and even-numbered crystals must together exhibit an anisotropy of approximately $\frac{1}{2}\lambda$ at the instant $t=0$ and $t=\frac{1}{4}$ T, and the respective alternating voltages applied to the odd numbered crystals in the sequence can be 90 degrees out of phase with the respective alternating voltages applied to the even numbered crystals.

On the Poincaré sphere shown in Figure 6a, the line FG indicates the principal direction of the crystal 55 and the line ED indicates the main direction of the crystals 54 and 56.

The initial orientation of the plane of polarisation of the linearly polarised beam incident upon the crystal 54 is arbitrary and is represented by the line A_0O, which is at an angle α to the axis FG.

At the instant $t=0$, only the crystal 55 is operative. The state of polarisation of the radiation emerging from the crystal 55 is found by a rotation of A_0 through 180° about the axis FG. The point A_1 on the equator represents the state of polarisation of the linearly polarised radiation emerging from the crystal 56.

At the instant $t=T/4$, only the crystals 54 and 56 are operative. The state of polarisation of the emergent radiation is found by a rotation about the axis DE through 180°. The point A_2 on the equator represents the state of polarisation of the linearly polarised radiation emerging from the crystal 56.

At the instant $t=T/8$, $V_1 = V \sin\omega t = V \sin 2\pi/T \; T/8 = 0.7$ V and $V_2 = V^1 \cos\omega t = 0.7\, V^1$.

The state of polarisation of the radiation emerging from the crystal 54 is found by rotation of the point A_0 through $0.7 \cdot 90° = 63°$ about the axis DE shown in Figure 6b. The point A_3 is thus reached. The state of polarisation of the radiation then passing through the crystal 55 is found by rotation about the axis FG through $2 \cdot 0.7 \cdot 90° = 126°$. This rotation is represented by the arc A_3A_4. Finally, the radiation passes through the crystal 56. The state of polarisation of the radiation emerging from the crystal 56 is found by rotation through 63° about the axis DE. The point A_5 near the equator is reached. The emergent light is substantially linearly polarised. The azimuth of the state of polarisation A_5 lies approximately midway between the azimuth for A_1 ($t=0$) and that for A_2 ($t=T/4$).

At the instant $t=3T/8$, $V_1 = V \sin\omega t = V \sin 2\pi/T. \; 3T/8 = 0.7$ V and $V_2 = V^1 \cos\omega t = -0.7\, V^1$.

Figure 6c indicates the points representing the state of polarisation after passage through the crystal 54 (point A_6), after passage through the crystal 55 (point A_7, obtained by rotation about the axis DE through

$-127°$) and after passage through the crystal 56 (point A_8), respectively. The point A_8 lies near the equator. The emergent light is again substantially linearly polarised. The point A_8 lies substantially at the same distance from the point A_1 ($t=T/2$) as from the point A_2 ($t=T/4$), cf. Figure 6a.

The series combination of the three KDP-crystals 54, 55 and 56 provide periodic signals which on approximation, since the third term and further terms of the mathematical series can be neglected with respect to the first two terms, can be represented by:

$$S_3 = \text{constant} + P \sin 2(\alpha_0 + \omega t) \text{ and}$$
$$S_4 = \text{constant} + P \cos 2(\alpha_0 + \omega t).$$

The orientation α_0 of the plane of polarisation of the linearly polarised radiation incident upon the series-combination can be detected from these signals in known manner, for example, by comparing the phase of one of these signals with that of the signal $V_1 = V \sin \omega t$.

Signals having a similar form to that of S_3 and S_4, are also obtained by employing the arrangement of Figure 1, in which a sawtooth voltage is applied to the crystal 5 from the source 10, the difference between the maximum and the minimum value of this voltage being so chosen that a change of phase difference of one wavelength is produced between the two waves formed from inherent linearly polarised light as it traverses the crystal 5.

The phases of the output signals thus obtained can be compared in known manner with the zero transits of the sawtooth voltage. When processing these signals, the detection system should be rendered inoperative during the short fly-back period of the sawtooth voltage.

In both of the embodiments herein described each electro-optical crystal or crystals can be made up of a plurality of component crystals to each of which a respective voltage can be applied which is smaller than the voltage that would have been applied to the equivalent undivided crystal by a factor proportional to the number of component crystals.

WHAT WE CLAIM IS:—

1. Apparatus for detecting the orientation of the plane of polarisation of an incident beam of linearly polarised radiation by means of a radiation-sensitive detection system comprising radiation-sensitive detection means to provide an output dependent on the orientation of the plane of polarisation of radiation incident thereon, and a series-combination of at least three doubly-refracting elements, at least one of which is an electro-optical crystal to which a varying electrical voltage is applied, said series-combination being arranged in the path of said incident beam prior to said detection means, the relative orientation of said elements and the electrical voltages applied to said electro-optical crystal or crystals being such that whereas the radiation falling on said detection means is maintained substantially linearly polarised, the orientation of the plane of polarisation is periodically varied with reference to the orientation of the polarisation of said incident beam to facilitate the determination of a stationary or slowly varying orientation of the polarisation of said incident beam.

2. Apparatus as claimed in Claim 1, in which said series-combination comprises two $\lambda/4$-plates and an electro-optical crystal arranged between said two $\lambda/4$-plates, the principal direction, as herein defined, of said electro-optical crystal being at an angle of 45° to the principal direction, as herein defined, of each of said $\lambda/4$-plates.

3. Apparatus as claimed in Claim 2, in which said varying voltage is a sawtooth voltage, the difference between the maximum and the minimum value of said sawtooth voltage corresponding to a phase anisotropy in said electro-optical crystal, of one wavelength of said linearly polarised radiation.

4. Apparatus as claimed in Claim 1, in which said series-combination comprises three electro-optical crystals, the principal direction, as herein defined, of the intermediate crystal being at an angle of 45° to the mutually parallel said principal directions of the two remaining crystals.

5. Apparatus as claimed in Claim 1, in which said series-combination comprises $(2n+1)$ electro-optical crystals, where n is an integer, so arranged that the principal direction, as herein defined, of each of the even-numbered crystals is at an angle of 45° to that of each of the odd-numbered crystals.

6. Apparatus as claimed in any one of Claims 1, 4 and 5, in which the varying voltage applied to the odd-numbered crystals of the series-combination and the varying voltage applied to the even-numbered crystals have a relative phase difference of 90°.

7. Apparatus as claimed in Claim 4, in which the amplitude of the voltage applied to each of the outer crystals corresponds to a change in path length difference of substantially one quarter wavelength in the relevant crystal, whilst the amplitude of the voltage applied to the intermediate crystal corresponds to a change in path length difference of substantially one half wavelength in this crystal.

8. Apparatus as claimed in any one of the preceding Claims, in which a said electro-optical crystal or crystals is or are made up of a plurality of component crystals to each of which a varying voltage is applied,

the amplitude of the voltage applied to each component crystal being smaller than the voltage that would be applied to the equivalent undivided crystal, by a factor proportional to the number of component crystals.

9. Apparatus for detecting the position of the plane of polarisation of a linearly polarised beam of radiation, substantially as herein described with reference to the accompanying drawings.

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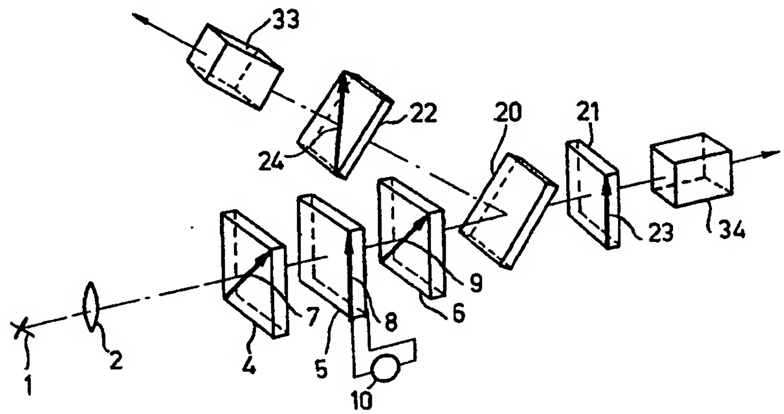

FIG.1

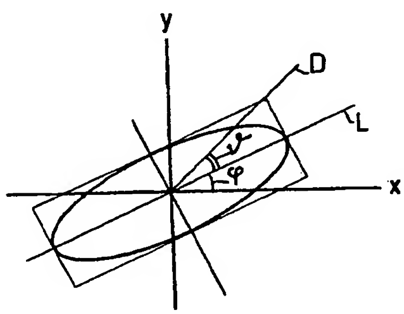

FIG 2a

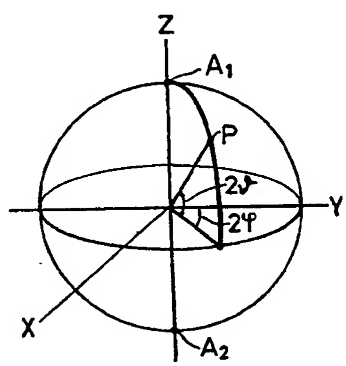

FIG.2b

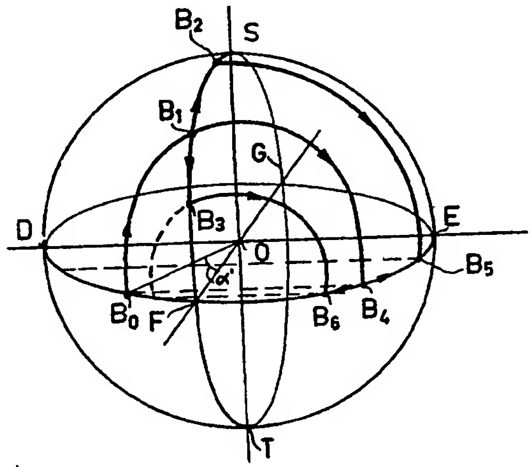

FIG.3

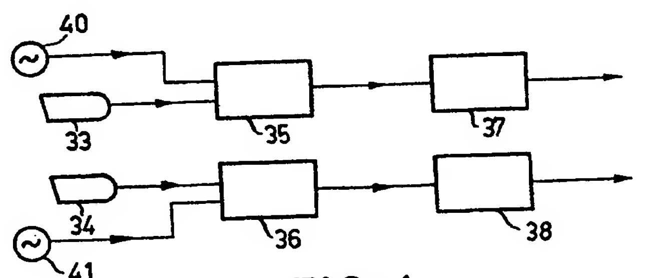

FIG.4

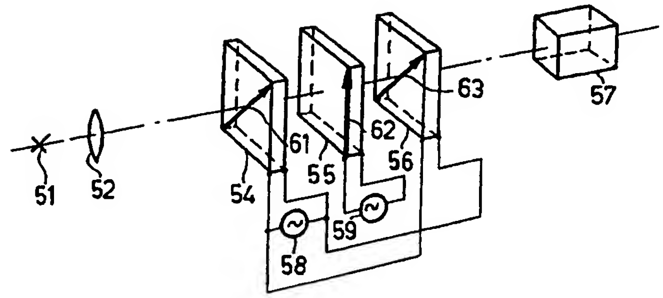

FIG.5

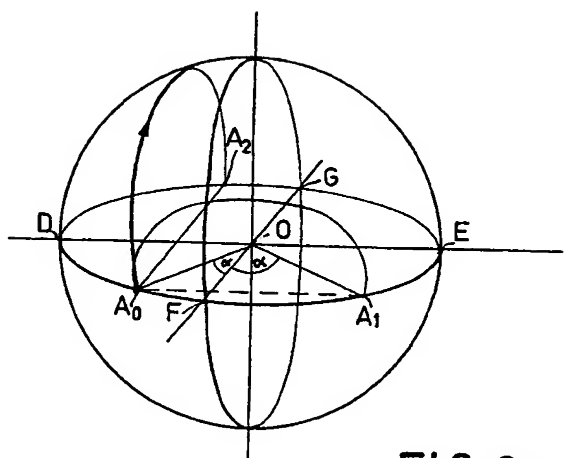

FIG.6a

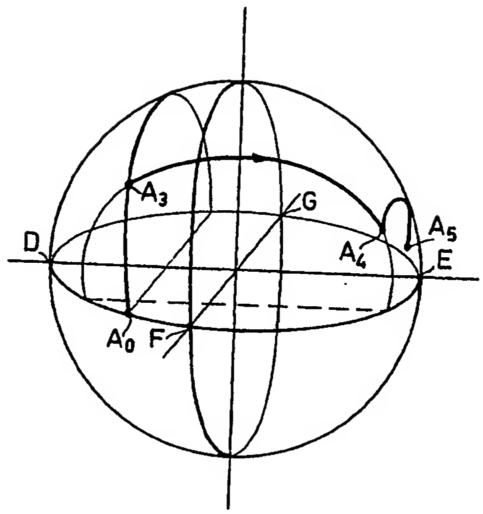

FIG.6b

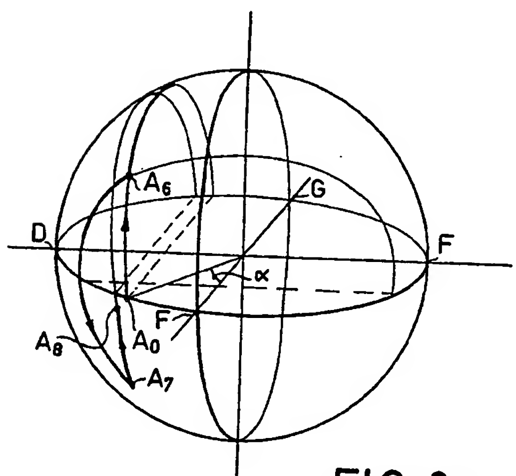

FIG.6c